nature portfolio

# Peer Review File

## The complexity of earthquake generation in nature: beyond cascade and pre-slip

*Web links to the author's journal account have been redacted from the decision letters as indicated to maintain confidentiality*

12th Apr 23

Dear Dr Martínez-Garzón,

Thank you for submitting a synopsis for a Review on "The complexity of earthquake generation in nature: beyond cascade and pre-slip". The synopsis is both interesting and well organised, and we'd be delighted for you to proceed along these lines.

When writing the article, please bear in mind that a good Review should provide fresh scientific insight, a novel synthesis of disparate data and an indication of where the field will move in the future. Of course, the Review should be fair and even-handed and cite more than your own work when summarising key findings.

Based on the feedback and suggestions I discussed internally with the Senior Editor Joe Aslin, we would like to suggest the following considerations before you proceed with preparing the full manuscript:

1. The integration of machine learning (ML) techniques has indeed opened up new possibilities for uncovering aspects of earthquake nucleation that were previously hidden. However, it is important for the piece to recognize the limitations of ML techniques, particularly when it comes to distinguishing the roles of certain physical processes that operate on long timescales, such as slab pull. We recommend that you provide an extensive explanation of the potential of ML techniques, while also clearly outlining their limitations. This would help to strike a balance between the potential advantages and drawbacks of using ML in this field.

2. Please consider adding an analysis of the Kahramanmaraş Earthquake Sequence. This suggestion is optional, as we understand that the data and understanding of this event may not yet be mature enough for adequate review. We leave the decision up to you as authors.

3. We would like to inform you that our Collection is expected to feature new articles that bring fresh insight into the Kahramanmaraş Earthquake Sequence. As such, once your full manuscript is submitted, we will make a decision on whether to include your piece in the Collection closer to the time. Please note that we could also publish your article without including it in the Collection.

Please keep these points in mind as you prepare your full manuscript, and address the specific feedback in your submission.

A description of the format requirements for Reviews in Communications Earth & Environment can be found here.

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** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

I look forward to reading your Review. Please don't hesitate to contact me if there's anything you would like to discuss in the meantime.

Best regards,

Luca Dal Zilio,
Editorial Board Member
Communications Earth & Environment

Joe Aslin
Senior Editor
Communications Earth & Environment

18th Sep 23

Dear Dr Martínez-Garzón,

Your manuscript titled 'The complexity of earthquake generation in nature: beyond cascade and pre-slip' has now been reviewed by two experts in the field. Reviewer #1 has additionally provided a PDF with further comments. Both sets of comments are appended below.

Before proceeding, I would like to extend my sincere apologies for the prolonged review process your manuscript has undergone. Due to the holiday period and the need to secure high-profile experts for a comprehensive review, the process took longer than anticipated. I understand the importance of timely feedback and regret any inconvenience this delay may have caused. Thank you for your patience and understanding.

You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns. In particular, please ensure that the revised manuscript meets the following editorial thresholds:

** Address structural and clarity concerns: Given that one reviewer found the manuscript difficult to follow due to its structure and repetitive sections, please reorganize your paper to improve its flow and readability. Cursory explanations should be elaborated upon to allow readers to grasp key concepts more easily. **

** Refine and justify methodological choices: Reviewers raised questions about the analytical choices made in compiling earthquake sequences and about the presentation of models. Please clarify these choices and justify their appropriateness, particularly focusing on the compiled sequence behavior and how they fit or don't fit existing models and theories. **

** Support all claims and interpretations with adequate evidence: Both reviewers emphasized the importance of substantiating your arguments. Ensure that your interpretations, particularly concerning the complexity of earthquake precursor processes, are fully supported by the data and studies you reference. Where this is not possible, please moderate your conclusions to reflect the level of existing support. **

We hope you will find the reviewers' comments useful as you decide how to proceed. Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at

Communications Earth & Environment or published elsewhere in the meantime.

We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

[link redacted]

** This url links to your confidential home page and associated information about manuscripts you may have submitted or be reviewing for us. If you wish to forward this email to co-authors, please delete the link to your homepage first **

Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Luca Dal Zilio
Editorial Board Member
Communications Earth & Environment

Joe Aslin
Senior Editor
Communications Earth & Environment

EDITORIAL POLICIES AND FORMAT

If you decide to resubmit your paper, please ensure that your manuscript complies with our editorial policies and complete and upload the checklist below as a Related Manuscript file type with the revised article:

Editorial Policy Policy requirements (Download the link to your computer as a PDF.)

For your information, you can find some guidance regarding format requirements summarized on the following checklist:(https://www.nature.com/documents/commsj-phys-style-formatting-checklist-article.pdf) and formatting guide (https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Martínez-Garzón and Poli provide a valuable overview on the topic of observations of earthquake precursors, that is the occurrence of seismicity and/or slow slip leading into an eventual rupture. By comprehensively considering dozens of earthquakes and published studies, they provide a timely assessment on this interesting and important topic. They suggest that the “vast majority of the slow-slip recordings before earthquakes represent tectonic transients or afterslip from large foreshocks, and hence they do not represent and intrinsic part of the earthquake self-nucleation”. The paper is well organized and researched and the quality of writing and the figures is high. Thus, I have unusually few and quite minor comments (in the returned PDF and listed below) and recommend publication following minor revisions.

Itemized comments, partly redundant with comments and edit suggestions in annotated PDF file:

Line 18: It might be good to clarify or reword what "unique evolution" means here. Is it a "unique evolution of observables prior to each individual mainshock" based on its unique conditions? That would certainly challenge the ability of recognizing and using precursory processes for short-term prediction applications.

Box 1, Loading rate: I think this loading rate effect is also evident in the behavior of repeating earthquakes during afterslip transients (e.g., Chen et al., 2010, doi:10.1016/j.epsl.2010.08.027)

Box 1, fluids: High pore-fluid pressure (reduced effective normal stress) has also been suggested to promote slow fault slip (e.g., Passelègue et al., 2020 NCOMMS and many others). Do you mean the type of processes suggested by Scuderi et al. (2017 EPSL) that may overcome this. Maybe this needs a bit more elaboration on how fluids and fluid pressure can both stabilize and destabilize slip?

Figure 2b, c: The number of events must be extremely dependent on the magnitude of completeness in a given area. Should this be done with a common minimum magnitude Mmin.

Lines 87, 280-281: Is there still broad support for the suggestion of EB1995 and their follow-up papers regarding a magnitude-dependent nucleation phase? I thought there were more recent studies that couldn't find evidence for this. It might be good to discuss the latest on this idea somewhere in the paper.

Line 312: replace "resembled" with "suggests that this is the afterslip"?

Figure 6a, b: It is quite hard to visualize such space-time scenarios (I have tried and failed myself). Many readers may think the X-axis is also space (i.e., that these are block diagrams, as is Fig. 6c). Would it work better to use color to indicate time? Alternatively, it may be better to get rid of the 3D “block-diagram” view and present these plots as simple x-time diagrams more analogous to Fig. 1.

I found the summaries of all the sequences considered in the supplement very valuable. Could you assign an event number (#1 etc.) to each earthquake and use that in the supplementary table 1 to allow for easy cross-reference.

Roland Bürgmann

Reviewer #2 (Remarks to the Author):

Review of “The complexity of earthquake generation in nature: beyond cascade and pre-slip” by Martínez-Garzón and Poli.

The manuscript reviews current theories of earthquake precursory processes and compiles information from published works on observations from 33 earthquake sequences to address the topic. The authors’ concluding thesis is that, other than some general sense that stresses increase before a mainshock, the complexity of the processes obscures any potential scaling relationships. While I was very interested to read this contribution because of the topic and the authors’ previous work in the field, I don’t think the authors’ concept came through in the final presentation of the material. I found the manuscript to be difficult to follow, with repetitive sections, cursory explanations of key ideas, and a summary section that seemed more appropriate to a proposal. Unfortunately, I think that it may be necessary to fully re-imagine and re-work the manuscript to make it suitable publication.

I provide some additional comments below, but these don’t address the broader structural issues with the manuscript noted above.

• Manuscript needs to be edited for English usage throughout.
• Analyses of sequences: The plots of compiled sequence behavior (number of events prior to the mainshock, radius of foreshock area) seem difficult to make any interpretations from due to differences in processing choices made by the authors of those studies.
• The initial listing of the models is hard to follow because the first two are in a separate bulleted list but the rest are embedded in the middle of paragraphs.
• In several places, the text refers in passing that some interesting info may be in a study rather than just state what it is (i.e. Line 148)

# The complexity of earthquake generation in nature: beyond cascade and pre-slip

Patricia Martínez-Garzón[1] and Piero Poli[2]

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## Abstract

Detection and analysis of earthquake precursory processes has concerned geoscientist from different disciplines over almost a century. Over the last years, dramatic improvements in earthquake monitoring, the integration of geodesy to capture slow deformation, and the incorporation of sophisticated data analysis techniques using e.g. artificial intelligence have allowed a more complete picture on how earthquake sequences evolve before the occurrence of the mainshock. We review the available seismological and geodetic analyses describing observations on precursory processes of 33 earthquake sequences covering a magnitude range $M_W$ [3.2, 9.1] that occurred on different tectonic regimes and stress conditions. We discuss the patterns that collectively emerge, with special emphasis on relating the available observations to the inferred physical processes driving the evolution of earthquake sequences. Our analysis highlights the strong role that various structural, tectonic and other boundary conditions play in the dynamics of the earthquake sequences, leading to a unique evolution of observables prior to the mainshock. From this, we propose the idea of earthquake preparation as a complex imbricated process, likely involving various juxtaposed driving physical mechanisms on different temporal and spatial scales.

## 1. Introduction

A persistent goal in geoscience is to improve protection against seismic hazard and risk. To advance this topic, scientists work to understand whether hazardous earthquakes show any kind of characteristic process (at short or long spatio-temporal scale) prior to mainshock initiation (e.g. Wyss, 1997; Bouchon et a., 2013; Mignan, 2014; Kato & Ben-Zion, 2020). Ideally, if such processes could be reliably and systematically observed prior to large earthquakes, automated near-real time data workflows could enable an extended warning time. However, the detection of earthquake preparatory and initiation processes, and understanding what they tell us remains a challenge in seismology. The current state of knowledge reflects a wide scatter among the available observations, including sequences with no detectable preparatory processes. The tectonic conditions that promote or inhibit detectable preparatory or nucleation processes prior to their initiation are still not well understood (e.g. Mignan, 2014; Gomberg 2018). Altogether, various lines of research still yield the outcome that earthquake prediction, if ever possible, still remains in the future of seismology (e.g. Mignan et al., 2014; Gualandi et al., 2020).

The physical and mechanical processes leading to earthquake initiation are nowadays well described from the theoretical and experimental point of view. In the laboratory, a whole body of early-stage work in the 80's permitted the observation of processes occurring before failures (e.g. Okubo and Dieterich, 1984; Scholz, 1998). These observations were supported by early fracture mechanics models (e.g. Rice 1983), which then evolved into widely accepted theoretical earthquake nucleation models, such as the rate-and-state (Dieterich 1992; Rice and Ruina, 1983) and the slip-weakening models (Rice, 1983). These models predict a *quasi*-static phase of deformation before earthquakes, during which the slip in the future rupture evolves from a stable sliding toward an acceleration (*pre-slip*). This *pre-slip* continues until a critical nucleation size characterized by a crack length $L_C$ is reached (Dieterich, 1992; Ohnaka, 1992). At $L_C$, instability in the system arises and the rupture grows *quasi*-dynamically, that is an earthquake is started. One focus of these models and laboratory experiments was to explore the effect of stress and materials heterogeneity within the area of *pre-slip* to understand the occurrence of foreshocks prior to earthquakes (e.g. Ohnaka, 1992). These heterogeneities included structural fault properties such as roughness (Ohnaka and Shen, 1999; Dresen et al., 2020; Cattania and Segall, 2021; Marty et al ., 2023), loading rate variation (Guérin-Marthe et al., 2019), effective confining pressure (Selvadurai et al., 2017), stress or material heterogeneities resulting in variable $L_C$ (e.g. Latour et al., 2013; McLaskey, 2019), fault strength (Passelègue et al, 2017) temperature or the presence of fluids (Cebry & McLaskey, 2021). A description of the properties and processes affecting the preparation and nucleation properties is given in Box 1.

If earthquakes in the laboratory are (to some extent) well understood, thanks to the overmentioned studies, less clear is our knowledge about the processes leading to an earthquake in real faults (e.g. Abercrombie and Mori 1995; Dodge et al 1996; Bouchon et al., 2011; Yao et al., 2020, Kato et al, 2012). Upscaling the physical models and observations from the lab to nature remains a challenge. This is mainly due to the inherent complexity of tectonic plates and faults, and to our incomplete understanding of the physical processes that cause earthquakes. There is also limited and heterogenous geophysical data available to characterize a number of earthquakes, especially if they occur in remote locations. Hence, many studies based on geophysical data reveal only sparse observations of the processes occurring before earthquakes, which often led to non-ambiguous interpretations (e.g. Bouchon et al., 2011; Ellsworth & Bulut, 2018; Gomberg, 2018).

In this work, we review a large number of studies focused on the analysis of geophysical data with the aim of illuminating collective patterns and the physical processes driving the occurrence earthquakes in nature. From our analysis, it emerges that (1) there is a plethora of processes causing stress changes on the fault that lead to the occurrence of an earthquake, and (2) these physical processes can occur juxtaposed at spatiotemporal scales spanning several orders of magnitude. To help the reader to follow our work, a Glossary of terms is provided, which defines the nomenclature that we will use in the text (Box S1).

| Properties exerting a role in the earthquake preparation and nucleation | |
|---|---|
| **Fault zone material composition** | Geodetic and seismological observations documented or suggested the occurrence of slow slip and/or pre-slip preceding some mainshocks. The fault zone material composition and its frictional properties can promote (i.e. a *velocity strengthening* medium) or inhibit (*velocity weakening* medium) the occurrence of slow slip (Rubin & Ampuero, 2005). For example, low-friction minerals rich in clay content are observed to favor velocity strengthening (Saffer et al., 2001; Kurzawski et al., 2016), while crystalline rocks without fault gauge are predominant in locked segments (Marone et al., 1990; Kaduri et al., 2016; Bürgmann, 2018). |
| **Fault roughness** | Fault roughness measures the deviation of a fault surface from planarity at all scales. Increased fault roughness is more representative to faults in nature and its effect on nucleation is documented in simulations (Tal et al., 2018; Cattania & Segall, 2021) and experimental work (Candela et al., 2011; Goebel et al., 2013; Harbord et al., 2017; Dresen et al., 2020; Guerin-Marthe et al., 2023). In rock deformation experiments, slow slip and foreshock rates were amplified |

| | |
|---|---|
| | by roughness (Dresen et al., 2020). In nature, however, direct measurements of fault roughness at seismogenic depths are typically not available. Recently, (Cochran et al., 2023) utilized the deviation of the seismicity from a planar fault surface to estimate the fault roughness associated to different faults in California. |
| **Fault segmentation** | Fault segmentation leads to more heterogenous fault properties and stress field (Mai & Beroza, 2002; Thakur & Huang, 2021). These structural heterogeneities exert a strong control on the amount of seismic energy release during the interseismic and coseismic periods. Increased geometrical complexities can also lead to the occurrence of slow slip (Romanet et al., 2018). In laboratory models, the occurrence of foreshocks and their spatial distribution is strongly controlled by the distribution of structural fault heterogeneities (Ohnaka, 1992). In nature, fault jogs, bends and step-overs have been observed to host numerous foreshocks for selected earthquakes in California (Dodge et al., 1995, 1996), in good agreement with the laboratory models. |
| **Pressure and temperature conditions** | The normal stress $\sigma_n$ typically increases with depth according to the weight of the overburden. Increased $\sigma_n$ suppresses small scale stress and fault heterogeneities, hence inhibiting the occurrence of foreshocks (Abercrombie and Mori, 1996). Temperature is thermodynamically linked with pressure. A strong variation on the slip behavior depending on these variables was already suggested in early nucleation models (Ohnaka, 1992). The $L_C$ was defined inversely proportional to $\sigma_n$ in the slip weakening framework (e.g. Campillo & Ionescu, 1997). This inverse dependence between $\sigma_n$ and $L_C$ was observed with frictional experiments in polycarbonate surfaces (Latour et al., 2013).<br><br>$\sigma_n$ also couples with fault roughness, generating an even broader spectrum of slip behaviors. Stick-slip slip experiments report larger duration of slip events and lower stress drops at lower $\sigma_n$ than their counterparts at higher $\sigma_n$ (Leeman et al., 2016, Harbord et al., 2017, Guérin-Marthe et al., 2023). Numerical simulations of faults described with a rate-and-state framework show that mainshocks tend to nucleate in the regions with higher $\sigma_n$, representing asperities (Cattania & Segall, 2021). |
| **Loading rates** | Laboratory frictional experiments in polycarbonates evidenced that the $L_C$ was inversely proportional to the speed at which the system accumulated displacement (loading rates, Guérin-Marthe et al., 2019). This means that, when the system is loaded more rapidly, it is more prone to rupture dynamically. The loading rate in the lab roughly corresponds to the tectonic loading rate in nature. A contrast between foreshock sequences of M > 6.5 interplate earthquakes and their intraplate counterparts was observed. Interplate earthquakes displayed accelerating seismic activity in the months to days prior to the mainshock, while this did not hold for intraplate settings (Bouchon et al., 2013). |
| **Presence of fluids and pore fluid pressure** | Fluids lubricate the faults facilitating slip, and increased pore fluid pressure reduces the effective normal stress, bringing a fault closer to failure. Laboratory experiments on various rock types shown that increased pore fluid pressure tend to promote velocity weakening frictional behavior over velocity strengthening, resulting in larger probability for earthquake ruptures (Scuderi & Collettini, 2016, 2018). In nature, fluid pressurization and migrations along faults have been suggested to explain different types of seismic evolutions. For |

| | |
|---|---|
| | example, it has been suggested that the 2009 L'Aquila (Lucente et al., 2010), the 2016-2017 central Italy earthquakes (Chiarabba et al., 2018) and the Iwate-Miyagi earthquake in Japan (Wang et al., 2008) occurred in fault patches that were over-pressurized by fluids. |

***Box 1:*** *Properties exerting a role on the preparation and nucleation of earthquakes, which can be decomposed into fault structural properties and boundary conditions affecting the rupture.*

## 2 Models describing earthquake preparation and nucleation

A combination of laboratory, field and theoretical studies converged to the formulation of two end-member models of earthquake nucleation, which predict the spatial and temporal evolution of stress and strength close to a main event. These models have been widely applied to describe the geophysical observations prior to an earthquake:

(1) The *pre-slip model* predicts aseismic slip acceleration prior to an earthquake. The acceleration takes place in a region called nucleation zone, with size related to the critical length ($L_C$), from which the earthquake dynamic rupture starts (Fig 1a, e.g. Ohnaka, 1992). It may be considered a self-nucleation model, from which the eventual observation of *pre-slip* indicates in advance that an earthquake is going to occur, hence allowing for earthquake predictability and possibly providing an estimate of its magnitude (Beroza and Ellsworth, 1996). Precursory aseismic acceleration has been observed in laboratory (Ohnaka and Shen, 1999) and numerical models (Ohnaka, 1992). This ~~model~~ has been also observed on smooth faults from large block experiments with very low normal stresses (e.g. McLaskey, 2019). In nature, scaling between the space occupied by foreshocks and the size of the incipient mainshock, was proposed as evidence for the nucleation size ($L_C$) for earthquakes (Ellsworth and Beroza, 1995; Dodge et al., 1996).

(2) The *cascade model*, in which the stress change associated to the occurrence of each foreshock triggers the next one, and eventually trigger the rupture of a larger earthquake by stress transfer (Fig 1b). In this model, earthquake nucleation is seen as a stochastic process in which every foreshock is no different than the mainshock. Therefore, the time and magnitude of the mainshock cannot be inferred prior to the end of the mainshock rupture (Ellsworth and Beroza, 1995), giving little chance for earthquake predictability (Münchmeyer et al., 2022).

The physical models described above have been frequently suggested to explain the seismic and geodetic observations prior to earthquakes in nature (e.g. Bouchon et al., 2011; Ellsworth and Bulut 2018; Kato et al, 2016). However, observations from several sequences also suggest that these two models likely oversimplify the real processes occurring in nature. For example, *pre-slip* is most observed in unnaturally homogeneous faults (McLaskey, 2019), something that is rarely found in nature. To account for the heterogenous nature of real faults, a novel body of numerical studies (Noda et al., 2013; Cattania and Segall, 2021) and laboratory settings (McLaskey, 2019; Yamashita et al, 2021) were developed. The introduction of stress and strength heterogeneity started to reveal complicated spatiotemporal patterns of foreshocks and aseismic slip, often resulting from stress feedback processes (e.g. Cattania and Segall, 2021). In these last described "*rate-dependent cascade-up*" models (3), the nucleation is characterized by the co-existence of stress transfer (as in the *cascade* model) and aseismic slip, even though the latter is not an intrinsic part of the nucleation process as for the *pre-slip* model. The heterogeneity in stress or strength is strongly controlling the style of precursory processes, and the nucleation of an event is favored by an increment of stress in a fault region prone to rupture.

Recent geophysical observations over longer spatial and temporal scales before large earthquakes highlighted a somewhat larger variability in the processes than that captured by the theoretical and laboratory models. Based on these observations, the *progressive localization* model (4) was proposed by Ben-Zion and Zaliapin, (2020), describing a progressive evolution from distributed damage in a rock volume towards a more localized slip. During this localization process, many clusters of seismicity are expected to be observed in a zone containing multiple faults on different scales. Each cluster can have its own foreshocks one of which might lead to the initiation of the mainshock rupture. In this model, the presence of an existing fault weaker than the surrounding medium is less (or not) relevant (Ben-Zion and Zaliapin, 2020).

Lastly, with the aim of generalizing the different existing models, Kato & Ben-Zion, (2020) proposed an *integrated model* (5) describing the generation of large earthquakes. The initial stage is equivalent to the *localization model,* with progressive generation of rock damage and ongoing seismicity along the future rupture area. Foreshocks are driven by the stress transfer from occurrence of previous seismicity or the presence of aseismic slip. Then, as in the *rate-dependent cascade-up* model, one foreshock may ignite the large dynamic rupture.

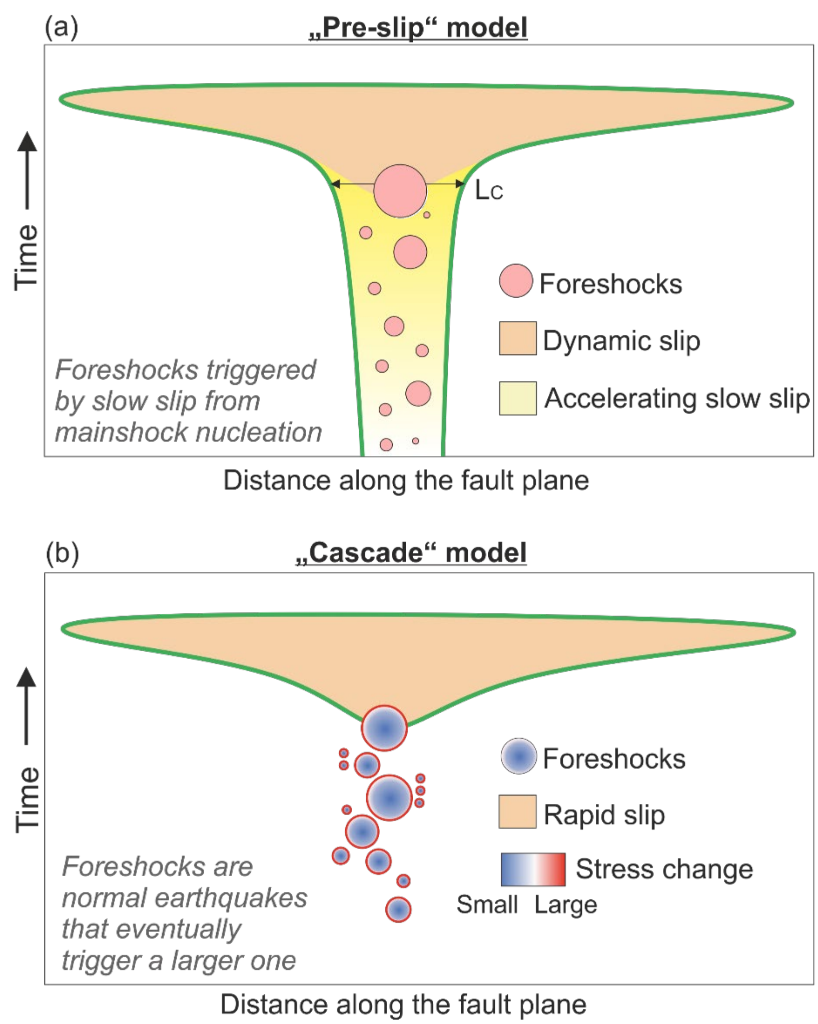

*Figure 1: The classical models for earthquake nucleation (after Ellsworth and Beroza, 1995): (a) "Pre-slip" model, (b) "Cascade" model. $L_C$: critical nucleation length.*

## 3. Earthquake precursory processes: synthesis from previous studies

We compiled available studies of earthquake precursory observations with the goal of summarizing the inferred physical processes potentially driving the occurrence of the mainshock. The 33 studied mainshocks (Fig 2a) span magnitudes from M 3.7 to M 9.0. The mainshock inventory includes earthquakes displaying diverse stress conditions, kinematics, and fault loading and structural conditions. When possible, quantitative parameters describing the sequences were extracted from the reviewed articles (Sup. Table S1). An individual description of each earthquake sequence is provided in Sup. Text 1.

### 3.1 Seismological observables

The reviewed studies reported on a plethora of seismological observations describing earthquake precursory processes captured with various monitoring methodologies. In most of these studies, the preparatory and nucleation phase is assessed from the space and time evolution of foreshocks. Rare are the cases in which a characterization of signals directly involved in the nucleation of an earthquake are presented (with a possible exception being e.g. Tape et al., 2018, See Minto Flats earthquake in Sup. Text 1).

As the source parameters and physics of foreshocks are a priori no different than mainshocks, there is no unique and unambiguous recipe to recognize foreshocks. In laboratory experiments, the beginning of the preparatory process is typically related to periods with visible non-elastic behavior in the stress-strain curve (e.g. Dresen et al., 2020; Marty et al., 2023). In nature, precursory activity is somehow identified as anomalous with respect to the stable stress or background seismicity conditions, but identifying the beginning of such stress increase is to date rarely possible. For this reason, most studies defined the foreshock sequences as all the seismicity with smaller magnitude than the mainshock over a subjective pre-defined time and space window (e.g. Shearer and Lin, 2009). However, the choice of the analyzed spatial and temporal scale strongly influences the physical processes that the studies were able to infer from the observations. The selection of these windows strongly varies among sequences and studies (e.g. Fig 2). For example, Kato and Nakagawa (2014) discussed foreshocks of the 2014 Iquique earthquake during ~4 months, while Kato et al., (2016) evaluated a longer foreshock sequence starting ~9 months before the mainshock. Applying more objective data analysis (Baiesi & Paczuski, 2004; Zaliapin & Ben-Zion, 2013) to the events preceding the Iquique earthquake helped to achieve a more rigorous estimation of the foreshock sequence (Aden-Antoniov, et al., 2020).

#### 3.1.1 Influence of monitoring conditions and data analysis

Ensuring that the monitoring conditions are sufficient to detect foreshocks is essential to correctly infer physical processes driving the dynamics of the sequences. Our mainshock compilation spans from the year 1986 to 2023. During these years, the seismic stations available to record seismicity have drastically increased in many of the analyzed regions, resulting in an overall decrease in the magnitude detection threshold of at least 1.5 units (see e.g. Hauksson and Shearer, 2005). In addition, developments in data analysis over the last decade, such as template matching (e.g. Shelly et al., 2006) and machine learning (e.g. Beroza et al., 2021) allowed further lowering the magnitude detection threshold, typically by a unit. The catalogs for the reviewed sequences were produced using different data analysis techniques, and using data recorded at seismic networks with varying detection thresholds, hence the magnitude of completeness significantly ~~varies.~~ Different data quality between catalogues complicates an objective comparison between foreshock sequences and may lead to differences in the foreshock rates. Furthermore, a high magnitude of completeness can obscure the illumination of spatio-temporal foreshock patterns. As reference, most monitoring setups capable to detect seismicity at least three magnitude units less than the mainshock, successfully detected foreshock activity (Mignan 2014).

The analyzed temporal window preceding the mainshocks from the selected sequences spans from 30 minutes (for the 2019 $M_W$ 6.4 Ridgecrest, Huang et al, 2020) to two years before (for the $M_W$ 7.8 Kahramanmaraş earthquake, Kwiatek et al, in review, Sup. Table 1). In Figs 2b, c, we report the number of seismic events preceding the mainshock, as a function of the duration of the analyzed time period, for the seismicity catalogs derived using standard and enhanced techniques, respectively. The scatter in the observations is larger using seismicity catalogs derived with standard techniques (Fig 2b) than using catalogs derived with enhanced techniques (Fig 2c). The scatter in the observations using enhanced catalogs (Fig 2c) is likely reduced with respect to standard catalogs (Fig 2b) by both the more sophisticated data analysis techniques and potential improvements in monitoring resolution. An example of this is evidenced by the difference between the initial catalog for L'Aquila earthquake in 2009, containing few hundreds of foreshocks (Chiaraluce et al., 2011), and a later template matching catalog which highlighted almost 5000 foreshocks within the same time interval (Cabrera et al., 2022).

Despite a larger consistency between foreshock rates and seismicity rates from different enhanced catalogs, a broad scatter is still present. For example, looking at approximately one day of recordings before mainshocks, the number of reported foreshocks included in enhanced catalogs vary from 50 to almost 200 (Fig 2b, c).

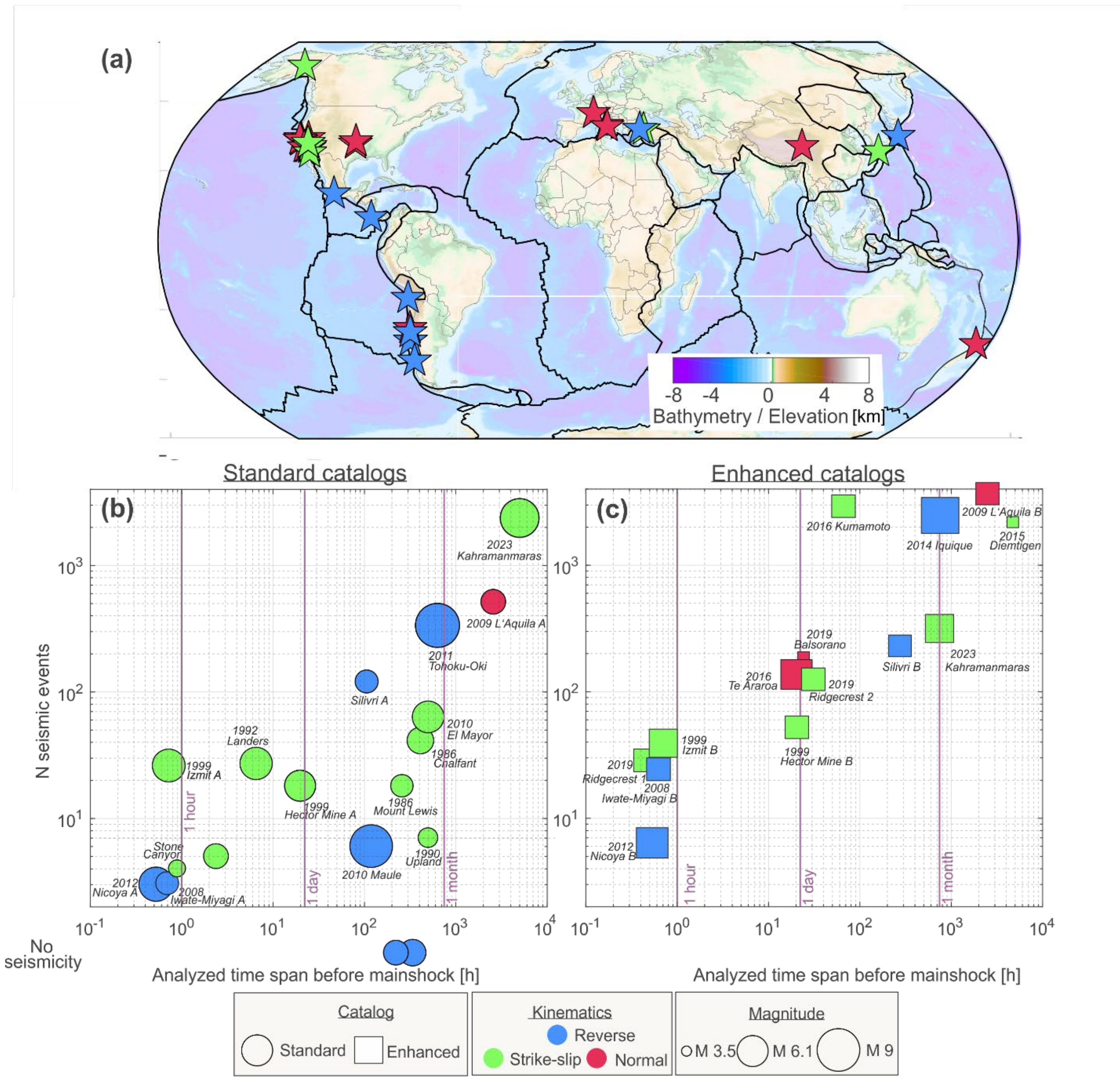


*Figure 2: (a) Location of the earthquake mainshocks (stars) included in this review analysis. Color is encoded with faulting style, with red, green and blue denoting normal, strike-slip and reverse faulting, respectively. (b, c) Number of seismic events preceding the mainshock vs analyzed time span using catalogs derived with standard (b) and enhanced (c) data analysis techniques, respectively. Symbol, color and size is encoded with the type of catalog, mainshock kinematics and magnitude, respectively. Lower part of the pictures contains events for which no foreshocks were identified during the analyzed time period.*

### 3.1.2 Foreshock dynamics from high-resolution catalogs

Once ~~that~~ the differences in the monitoring conditions and data analysis among sequences are minimized, the variability in the precursory observations, including foreshock rates, moment release and the size of the foreshock area (Figs 2, 3) might reflect various different physical processes ~~on~~ the lead up to an earthquake. Even by just selecting high-resolution catalogs we still observe a broad range of physical processes proposed in the analyzed articles, to explain the observations. The studies also suggest the coexistence of processes as for the 2016 Te Araroa sequence, which began with a $M_W$ 5.7 foreshock that increased the Coulomb stress by 1 kPa on the future mainshock area (Warren-Smith et al., 2018), but the authors also hypothesized ~~on~~ the occurrence of a potential slow slip event, which would have gone undetected due to the remote and offshore location of the sequence.

Monitoring the time-space foreshocks ~~evolution~~ is a common feature for the studied sequences, and can provide valuable information about ~~its~~ driving physical mechanism(s) (e.g. Dodge et al., 1996; Kato et al., 2016). The foreshock~~s~~ temporal evolution from the analyzed studies highlighted the complexity of the physical processes before a mainshock. If foreshocks were a by-product of a single process, a specific time or seismic moment evolution would be expected, such as accelerating seismic release (e.g. Hough, 2010; Mignan 2011). However, a simple time or energy evolution (e.g. acceleration) is rarely observed. An exception is the 2023 Kahramanmaraş earthquake, which does display accelerating seismicity rates surrounding its nucleation area (Kwiatek et al., in review), although the acceleration mostly happened due to selected nearby clusters. In fact, in most cases the foreshocks occur in intermittent temporal clusters each of which can represent the seismic expression of different physical processes (Fig 3a, b). For example, the 2009 L'Aquila and 2019 Marmara foreshock sequences revealed several temporal seismicity increments (Fig 3a, b) which are partly related to fluid migration or aseismic slip, partly related to the afterslip from large foreshocks and partly indicative of stress interaction between asperities (Durand et al., 2020; Cabrera et al., 2022).

The temporal clustering of foreshocks is often accompanied by spatial patterns, which are strongly variable as function of time to the mainshock (Fig 3c, d). Linear or diffusive spatio-temporal migrations can sometimes be observed and related to various physical mechanisms such as aseismic slip (Perfettini and Avouac, 2004), fluid migration (Shapiro et al., 2003) or stress transfer between earthquakes (Ellsworth and Bulut, 2018). The speed of migration (e.g. Chen and Shearer, 2013; Fischer and Hainzl, 2021), can help to distinguish between the different mechanisms. For nine of the sequences, foreshock spatio-temporal migrations with velocities varying from 2 m/day to 20 km/day were reported (Table S1). Migration velocities in the order of < 1 km/day are typically interpreted as a signature of fluid movement and diffusion (e.g. as in the 2016 Pawnee earthquake, Chen et al., 2017 or the 2010 El Mayor-Cucapah earthquake, Yao et al, 2020). Faster migration velocities are commonly associated with the propagation of slow slip (e.g. as the 2016 Kumamoto earthquake, Kato et al., 2016a or the 2014 Iquique earthquake, Kato et al, 2016b). However, commonly the interpretation of these migrations is non-unique (Gomberg, 2018). For example, a spatial clustering of hypocenters may be observed also in foreshock sequences driven by stress transfer (e.g. Ellsworth and Bulut, 2018).

The clearest behavior that we observe among different sequences is that foreshocks tend to occur in intermittent spatio-temporally localized clusters that interact with each other and point towards the weakening of an entire area. The evolution of Acoustic Emissions (AE) recorded in rock deformation experiments is often found to follow a comparable evolution. There, on the lead up to the fault stick-slip, several bursts of AE events are typically observed to localize in multiple asperities which coalesce as fracture approaches (Dresen et al., 2020; Marty et al., 2023). Despite the progress of the data analysis techniques aided by artificial intelligence to generate enhanced seismicity catalogs, such techniques are still far from being able to separate the seismicity driven by different physical processes.

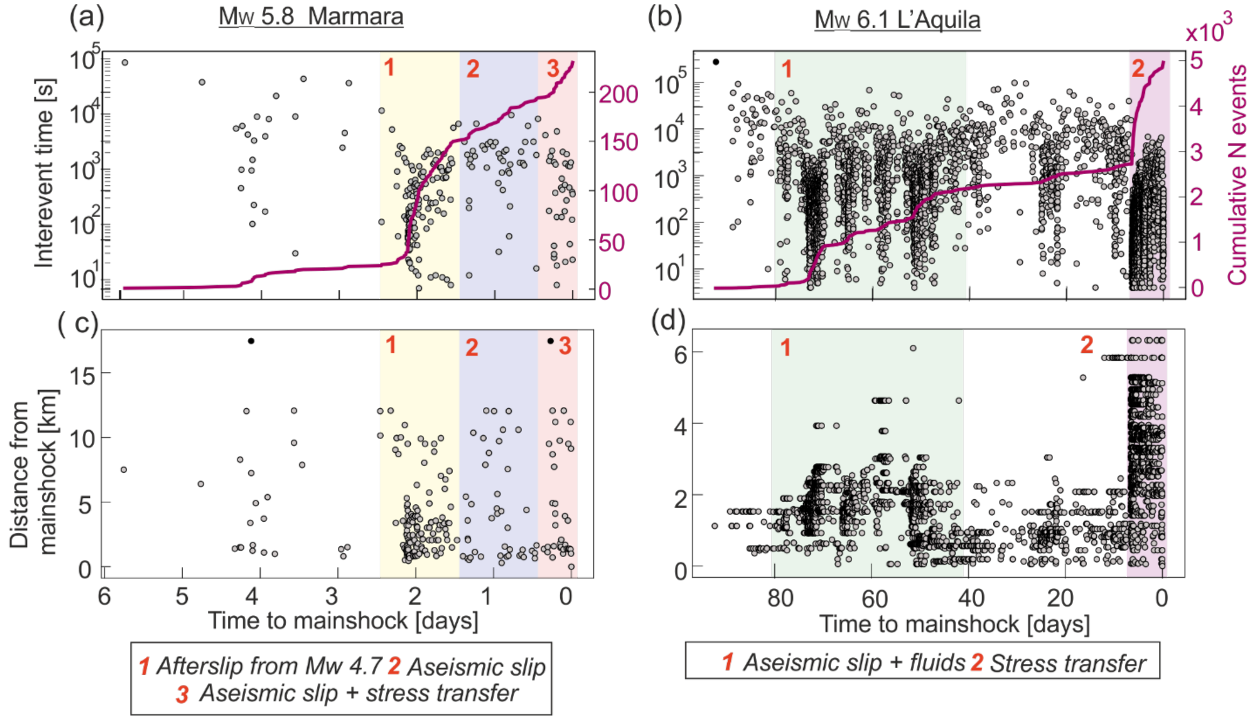


*__Figure 3:__ Foreshock evolution as function of time and distance to mainshock for the 2019 $M_W$ 5.8 Marmara and 2009 $M_W$ 6.1 L'Aquila sequences. (a,b): interevent time as function of time to mainshock (grey circles) and cumulative number of events (purple line). Concentrations of grey circles reveal seismicity accelerations. (c,d): Distance as a function of time to mainshock. In periods of accelerated seismicity, spatial clustering is also observed. Colored boxes mark seismicity clusters discussed in Durand et al., (2020) and Cabrera et al., (2022), with their inferred physical mechanism reported in the legend.*

### 3.1.3 Mainshock size and foreshock area

In the *pre-slip* nucleation model, foreshocks are a by-product of a growing slow slip, and they rupture small brittle asperities within the slow slip area (Fig 1a). Therefore, in principle, the area covered by the foreshocks could provide insights on the critical nucleation length $L_C$ of the mainshock, and hence, of its magnitude. Dodge et al., (1996) estimated the activated area by the foreshock sequences of six mainshocks (assuming a constant stress drop of 3 MPa) and compared the radius of the foreshock area with the mainshock coseismic moment. They found that the extent of the foreshock sequences, representing the size of the nucleation region, scaled with mainshock moment in the same way as determined independently from measuring the duration of the seismic nucleation phase (Ellsworth & Beroza, 1995). Increasing the number of observations with our additionally compiled sequences still shows that the size of the area activated by the foreshocks tends to increase with mainshock size (Fig 4). However, several sequences with an enhanced seismicity catalog available do not follow such trend. Among them, the foreshock sequences from strike-slip mainshocks such as the 1999 $M_W$ 7.1 Hector Mine, the 1992 $M_W$ 7.3 Landers or the 2019 $M_W$ 6.4 first Ridgecrest mainshock, activated a smaller area than predicted by the overall trend (Fig 4). These mainshocks invoke a potential rupture driven by more localized physical processes, such as static stress transfer. Conversely, the foreshock sequences of the 2014 $M_W$ 8.1

Iquique and 2017 $M_W$ 6.9 Valparaiso subduction earthquakes activated a broader area that what predicted by this empirical trend (Fig 4). This has been interpreted as a signature for aseismic slip loading and fluid migrations.

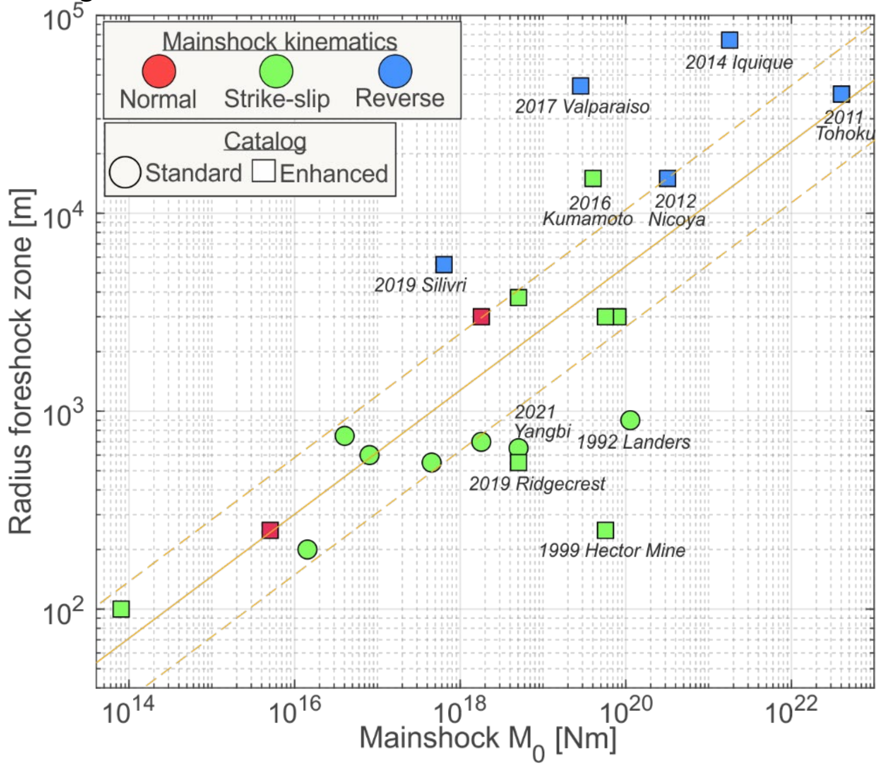


*Figure 4: Estimated radius of the epicentral foreshock area vs mainshock coseismic moment. Color is encoded with the mainshock kinematics. Solid and dashed orange lines represent a linear fit to the data and 1 standard deviation, respectively (after Dodge et al., 1996; Yoon et al., 2019).*

### 3.2 Geodetic observations of slow-slip preceding earthquakes

A complex spatio-temporal evolution is also recovered from geodetic observations before mainshocks. If a single process with a specific time evolution was taking place prior to an earthquake (e.g. acceleration of slip, Mignan 2011), we would see its signature directly on the recorded geodetic deformation. However, none of the reviewed studies reported unambiguously this sole behavior. Hence, geodetic observations also support the notion of several physical processes driving the occurrence of earthquakes. An outcome of our review is that the vast majority of the slow-slip recordings before earthquakes represent tectonic transients or afterslip from large foreshocks, and hence they do not represent and intrinsic part of the earthquake self-nucleation.

One of the most complex GNSS observation is reported before the 2011 $M_W$ 9.0 Tokohu-Oki earthquake. Prior to the mainshock, a slow transient was recorded in the GNSS instruments, beginning ~2days before the mainshock following a $M_W$ 7.3 foreshock (Kato et al., 2012; Hino et al, 2014). The recorded deformation was initially inferred to be aseismic *pre-slip* and hence as an observable of self-nucleation (Kato et al., 2012). Nevertheless, the log-like temporal decay of the slip resembled the afterslip from the $M_W$ 7.3 foreshock (Otha et al., 2012). Inversion of GPS data revealed how afterslip located up-dip of the $M_W$ 7.3 foreshock was the most likely explanation for occurrence of foreshocks and repeating earthquakes prior to the $M_W$ 9.0 (Kato et al., 2012). Hence, this recorded aseismic slip (afterslip) is not "*pre-slip*" representing an intrinsic process of the incoming $M_W$ 9.0, mainly because it did not occur within the future mainshock rupture, and it also decayed with time instead of accelerate. Nevertheless, this aseismic slip most likely contributed to increase the stress in the future mainshock area and thus to nucleate the 2011 Tohoku-Oki earthquake (Otha et al., 2012, Kato et al., 2012).

Another evidence of complex interplay between different slow slip processes before earthquakes emerged from geodetic studies of the deformation prior to the 2017 $M_W$ 6.9 Valparaiso earthquake (Ruiz et al., 2016; Caballero et al., 2021). The event was preceded by significant slow deformation recorded by geodetic data, and further evidenced by the occurrence of repeating earthquakes (Ruiz et al., 2016; 2017). This aseismic slip did not display clear acceleration with time, but it initiated after a $M_W$ 6 foreshock and decayed temporally, suggesting again the occurrence of afterslip, as before the Tohoku 2011 earthquake. However, the slip balance in between foreshocks and aseismic slip done by Caballero et al. (2021), showed that seismicity and afterslip could account for only half of the observed slip. The remaining aseismic slip was suggested to represent *pre-slip* related to the initiation phase of the $M_W$ 6.9 mainshock. Further studies will be needed to verify the nature of this observed slip.

### 3.3 Large scale processes

Most studies targeting earthquake preparation and nucleation focused on temporal scales spanning from minutes to months and spatial scales ranging from meters to tens of kilometers around the mainshock hypocenter. This choice was probably driven by the aim of capturing the short-term slip acceleration predicted by theoretical models (e.g. Ohnaka, 1992), and was also likely imposed by the lack of continuous geophysical time series covering long time periods.

With the collection of decades-long geophysical data over entire plate boundary regions, scientists began to search for larger scale and longer-term signatures of processes leading to major earthquakes. From the analysis of seismic catalogs (Bouchon et al., 2016) and geodetic time series (Bedford et al., 2020) in Japan and Chile at the plate boundary scale, authors reported a long-term (months to years) slab pull effect which favors the occurrence of large earthquakes. Other studies highlighted how stress transfer from distant earthquakes (100-1000km) can affect the fault coupling in some region of the megathrust (e.g. Ruiz et al., 2017, Ruiz et al., 2016), promoting the weakening of the interface (Melnick et al., 2017, Ruiz et al., 2017, Ruiz et al., 2016). A similar behavior was recently observed in laboratory analogue of subduction zone (Corbi et al., 2022). Earthquake preparation over large spatio-temporal scales has also been investigated in transform faults that are locked during the interseismic period. Ben-Zion and Zaliapin (2020) took advantage of the decades-long seismicity catalog of Southern California, to show that at least four of the largest recent earthquakes in southern California were preceded in the previous decades by generation of off-fault rock damage around the eventual rupture zones. Seismicity localization around the main fault planes starting 2-3 years before the mainshocks was also reported.

## 4. A conceptual model for earthquake preparation and nucleation

We shown that the processes observed before mainshocks are affected by the resolution of the monitoring setup, the choice of temporal and spatial windows of analysis and the data analysis techniques. However, in addition to these issues, the reported observations also suggested a genuine complexity in the physical processes leading to an earthquake.

A general outcome of our review is that most studies revealed a stress increase in the future mainshock rupture area. This stress increase may be due to a large variety physical processes, some of them juxtaposed (e.g., Radiguet et al., 2016; Ellsworth and Bulut, 2018; Kato and Ben-Zion, 2020). This imbricated ensemble of processes acts over different time and spatial scale, and it is likely controlled by a broad spectrum of heterogeneities (rheological and geometrical, among others) which make the preparation phase of each mainshock to some extent unique. This complexity can also explain the lack of scaling for several of the parameters that we extracted from the reviewed studies (Table S1). Therefore, we propose a conceptual model in which the preparation and nucleation of earthquakes is influenced by a wide range of physical processes, sometimes juxtaposed, acting over different temporal and spatial scales (Figs 5, 6).

Among the reviewed studies, almost no sequence reported observables which can directly be related with the earthquake self-nucleation (with possible exceptions being Tape et al, 2018, and to some extent, Caballero et al., 2021). This suggest that if observable self-nucleation processes, as those resolved in laboratory experiments are present in nature, their detection is very hard, as their associated signals are likely too small in amplitude or too short in time, and often convolved with other processes to be systematically identified by our current instrumentation and data analysis techniques.

Foreshocks are the most distinct signature of earthquake precursory activity (e.g., Abercrombie and Mori, 1996; Dodge et al., 1996). Most studies support the notion that foreshocks are a byproduct of external processes altering the state of stress in a given fault and reflecting its heterogeneities. Only rarely we observe foreshock accelerations as predicted by numerical modeling or in some laboratory experiments (Ampuero & Rubin, 2008; Dieterich, 1992; Rubin & Ampuero, 2005; Dieterich & Kilgore, 1996; McLaskey, 2019; McLaskey & Kilgore, 2013; McLaskey & Lockner, 2018; Cattania and Segall, 2021). When it occurs, acceleration is observed at regional scale rather than being part of a localized process (e.g. Kwiatek et al., in review). Their occurrence in bursts is likely to represent surges of creep (Cattania and Segall, 2021), fluid pressure variations (e.g., Lucente et al., 2010), or time clustering associated with static and dynamic triggering (e.g., Ellsworth and Bulut, 2018; Yoon et al, 2019). In the laboratory, analogous complexity in the observations and feedback between different processes is more evident when rupturing fault interfaces with many asperities of variable roughness (e.g., Gounon et al., 2022).

The evolution of stress at the future mainshock hypocenter is additionally affected by extra external processes such as seasonal, and multiannual stress variations (e.g., Johnson et al., 2017), and tidal stress evolution (e.g., Tanaka, 2010; Martínez-Garzón et al., 2023) which can both promote or inhibit the stress build up on the fault, and hence, the nucleation of earthquakes. Finally, anthropogenic activities such as mining of the subsurface, fluid injection and extraction, or reservoir impoundment can also perturb the stress field over a broad spatio-temporal scale from the source region. These additional sources of stress perturbation add to the ones discussed in our work, further complicating the time-dependent stress state of a fault (Fig. 5, 6).

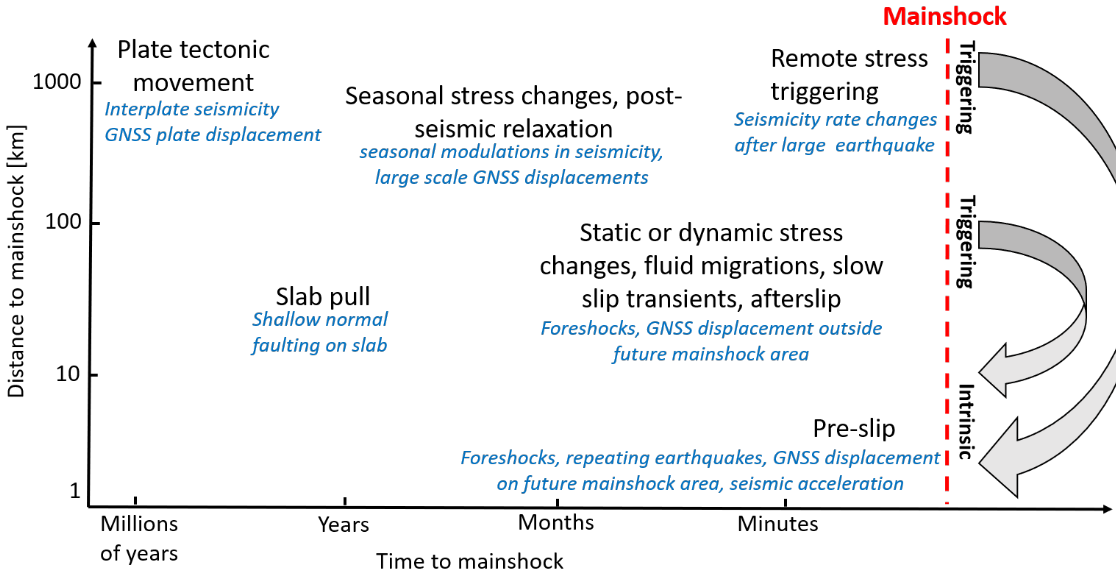


***Figure 5:*** ~~*Table*~~ *summarizing some of the identified physical processes (in black font) and seismological and geodetic observables (blue italic font) occurring before mainshocks at various spatial and temporal scales with respect to the mainshock.*

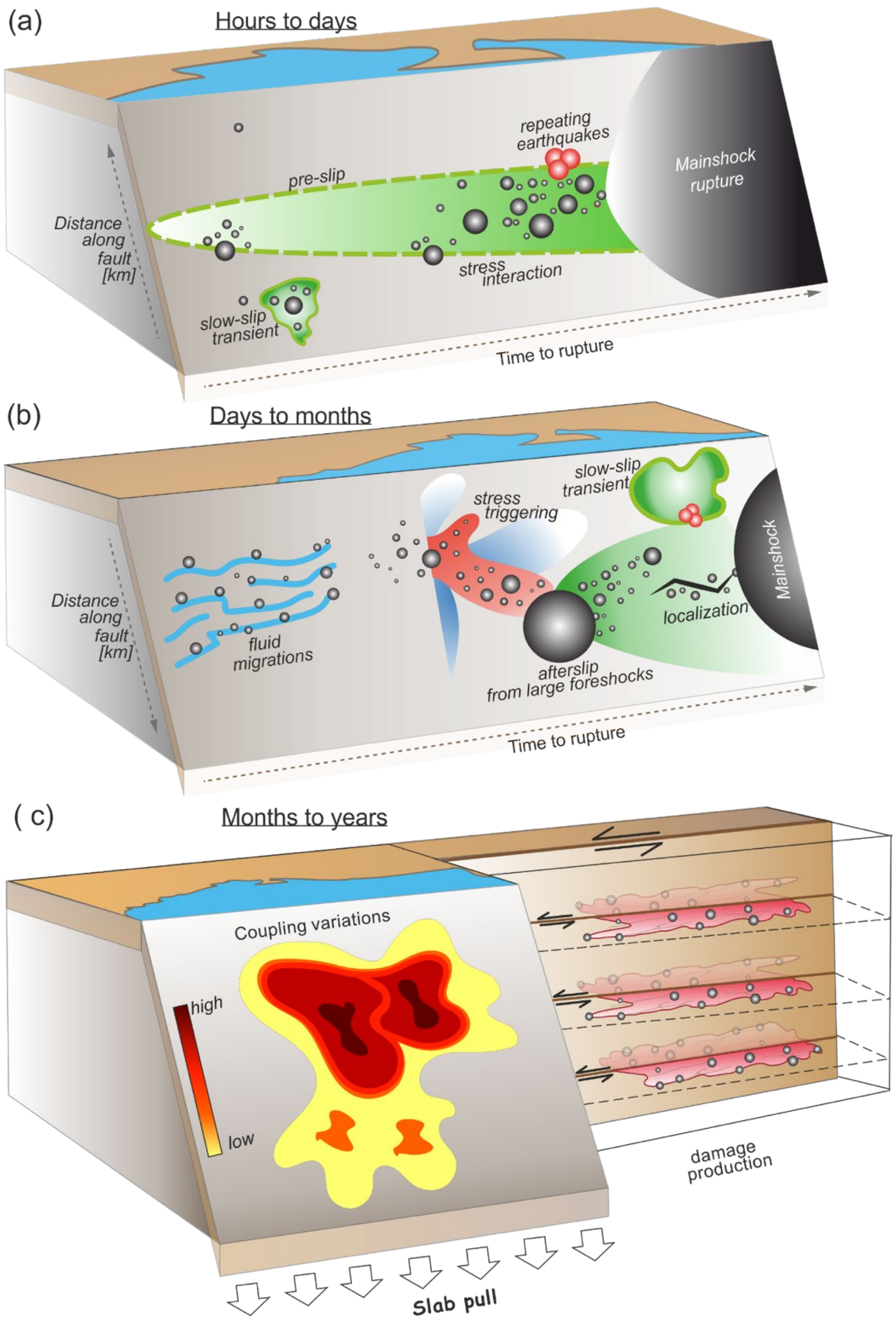


***Figure 6****: Conceptual sketch illustrating some of the physical mechanisms at different spatio-temporal scales that may be involved on the preparation and nucleation of an earthquake. Temporal scales (a) from hours to days, (b) from days to months and (c) from months to years, approximately.*

## 5. Summary and research perspectives

Decades of research on how earthquakes in nature start point towards a wealth of physical processes over different temporal and spatial scales that promote the occurrence of a mainshock and play a role in controlling the observable seismic and slow precursory activity. Detailed studies of observable slip processes prior to earthquakes in recent years constitute a step forward in documenting the complexity involved in the development of each earthquake sequence, and can now serve as examples ~~to~~ a more systematic evaluation of future mainshocks initiation. What emerges from our review is that in most cases, several physical processes act superimposed, with their effects on the stress field widely varying in space and time. Hence, each earthquake is likely to have its own preparation history, which results from the contribution of different physical processes, and boundary conditions. ~~From it,~~ we propose the view of the earthquake preparation and nucleation as a complex process, involving several temporal and spatial scales. How these processes are illuminated can be strongly affected by the available monitoring setup for each sequence, as well as for the selected spatial and temporal scales of analysis.

To shed new light into the preparation and nucleation of earthquakes, a joint effort between laboratory experimental studies, development of theoretical models and refining the monitoring of observables in nature is needed. Here we summarize some aspects that we consider most relevant to success in this endeavor.

(i) **Densify near-fault monitoring:** Densifying near-fault seismic and geodetic monitoring is the most pressing need to get insights into the fault activity prior to mainshock ruptures (e.g. Ben-Zion et al., 2022). Improving the resolution can enable the detection and characterization of smaller foreshock activity, or resolve geodetic signatures of aseismic processes or fluid movements, hence illuminating the underlying mechanisms more clearly (e.g., Mignan, 2014). An optimal seismic monitoring network can greatly contribute to illuminate the fault behavior prior to a large earthquake, as it has recently been illustrated with the 2023 $M_W$ 7.8 Kahramanmaraş earthquake sequence (Kwiatek et al., in review). As we witness that large earthquakes not only nucleate along main faults but also on secondary branches, these efforts should not be limited exclusively to main fault zones, but span the plate boundaries.

(ii) **Next-generation observables of fault processes over various frequency bands**: Together with the necessity of instrumental development, there is the need of including cutting edge data. So far, we have seen how enhanced seismicity catalogs with lower detection thresholds are effective in illuminating what happens before the mainshock rupture (i.e., Fig 2). A necessary step is to continue generating enhanced observations for past and future earthquakes spanning various magnitudes, faulting styles and background stress conditions, with the aim of extracting similarities and differences among sequences. To this end, data analysis techniques employing artificial intelligence have a tremendous potential to boost observation of fault signals (e.g. Bergen et al., 2019; Mousavi et al., 2020; Beroza et al., 2021), which, in turn, can lead to clearer observables of earthquake preparatory processes.

(iii) **Automated multiparametric and multi-scale workflows:** With high-resolution data and cutting-edge methods there will be the need of developing and testing automated workflows based on time-series of parameters (Rouet-Leduc et al., 2017), or data features (Shi et al., 2021; Seydoux et al., 2020; Hulbert et al., 2019), covering a wide range of spatio-temporal scales. Such workflows might shed some lights on which physical processes are most important in the preparation and nucleation of each mainshock, and at which scales these processes are most resolvable, and might help to distinguish in between the different juxtaposed physical processes acting at various spatio-temporal scales.

(iv) **Identifying the beginning of the preparatory phase:** In laboratory experiments, the beginning of the preparatory phase is typically considered as the time at which the stress-strain curve departs from the elastic regime and the sample deforms non-linearly. A promising research target is to identify whether the observables that we are able to monitor on faults in nature (e.g., bursts of seismicity, geodetic signals, increased energy release) are anomalous with respect to the stable conditions, and hence, represent part of the preparatory stage. For example, being able to distinguish whether a burst of earthquakes will likely not continue further (developing what we ~~know~~ call a swarm) or, if, in contrast it may continue destabilizing a fault towards a large rupture. To this end, experiments in underground laboratories under controlled conditions have the potential to bridge the gap between the controlled conditions of laboratory experiments and the larger heterogeneity and complexity imposed by faults in nature.

(v) **Revised physical frameworks describing earthquake nucleation**: Some well-recorded earthquake preparatory processes from experiments and nature point towards complex interaction and feedback between localized seismicity clusters around the future mainshock, and a complex interplay between seismic and aseismic deformation. This complex behavior is not yet well reflected in commonly used physical frameworks describing earthquake nucleation such as the rate-and-state or slip weakening models. Hence, there is a need to revisit these frameworks according to the new observations, perhaps allowing to include a stronger level of complexity or larger spatial and temporal scales.

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**REVIEWER COMMENTS**

**Reviewer #1 (Remarks to the Author):**

Martínez-Garzón and Poli provide a valuable overview on the topic of observations of earthquake precursors, that is the occurrence of seismicity and/or slow slip leading into an eventual rupture. By comprehensively considering dozens of earthquakes and published studies, they provide a timely assessment on this interesting and important topic. They suggest that the "vast majority of the slow-slip recordings before earthquakes represent tectonic transients or afterslip from large foreshocks, and hence they do not represent an intrinsic part of the earthquake self-nucleation". The paper is well organized and researched and the quality of writing and the figures is high. Thus, I have unusually few and quite minor comments (in the returned PDF and listed below) and recommend publication following minor revisions.

Reply: We thank the Reviewer for the evaluation of our work and the constructive feedback provided. In this new version, we have addressed all raised concerns and explained them below in a point by point protocol.

Itemized comments, partly redundant with comments and edit suggestions in annotated PDF file:

Line 18: It might be good to clarify or reword what "unique evolution" means here. Is it a "unique evolution of observables prior to each individual mainshock" based on its unique conditions? That would certainly challenge the ability of recognizing and using precursory processes for short-term prediction applications.

Reply: Thank you for the comment. Indeed, the word "unique" in the previous context had strong implications in the context of earthquake prediction. As this is not a topic that is strongly addressed in this manuscript, we have reworded the sentence as follows:

"*Our analysis highlights the strong role that different structural, tectonic and other boundary conditions play in the dynamics of the earthquake sequences, and hence, in the seismic and geodetic observables prior to the mainshock.*"

Box 1, Loading rate: I think this loading rate effect is also evident in the behavior of repeating earthquakes during afterslip transients (e.g., Chen et al., 2010, doi:10.1016/j.epsl.2010.08.027)

Reply: Thank you for pointing this out, we have now added here a brief description of the effect of slow transients representing afterslip (and signifying changes in the loading rates) on the recurrence times and seismic moment release of earthquake repeater sequences. In particular, we have added the following sentences:

"*The effect of loading rates has also been demonstrated in the behaviour of repeater sequences during afterslip transients. Following the 2004 Parkfield M 6 earthquake, local earthquake repeating sequences displayed greatly reduced recurrence times that gradually increased thereafter (e.g. Chen et al., 2010). Similar behaviour has been observed in the creeping segment of the Main Marmara Fault (Becker et al.,* *2023).*"

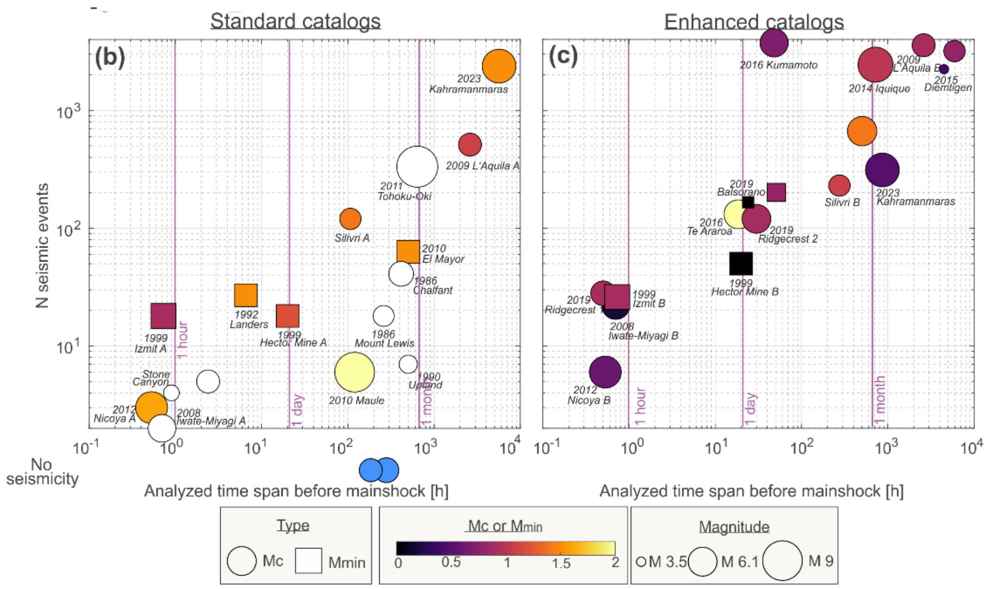
Box 1, fluids: High pore-fluid pressure (reduced effective normal stress) has also been suggested to promote slow fault slip (e.g., Passelègue et al., 2020 NCOMMS and many others). Do you mean the type of processes suggested by Scuderi et al. (2017 EPSL) that may overcome this. Maybe this needs a bit more elaboration on how fluids and fluid pressure can both stabilize and destabilize slip?

Reply: Thank you for pointing this out. In this version of the manuscript, we have now extended the description of the role of fluids and pore pressure in earthquake nucleation, to more accurately describe the different effects of the pore fluid pressure, which can both stabilize and destabilize the faults and promote slow and fast slip. Specifically:

"*However, an increase in pore fluid pressure does not necessarily lead to dynamic rupture and has also been observed to play a key role in promoting slow slip on faults (e.g., Guglielmi et al., 2015). This behavior has typically been explained by a dependence of Lc on fluid pressure, which is explicitly assumed in both slip weakening and rate-and-state theories (e.g. Viesca and Rice, 2012; Marone, 1998). Recent experimental work has also shown that variations in the pore fluid pressure, which affect the initial effective normal stress, can generate the entire spectrum of slip behavior (Passelegue et al., 2020)*".

Figure 2b,c: The number of events must be extremely dependent on the magnitude of completeness in a given area. Should this be done with a common minimum magnitude Mmin.

Reply: Thank you for this comment. We agree that this plot should depend, among other factors, on the corresponding magnitude of completeness ($M_C$). To more explicitly visualize the variations in $M_C$ between sequences, we reviewed and compiled this parameter from the relevant studies. We then updated the Figures 2b,c to encode the colour with the corresponding given $M_C$. Unfortunately, this parameter was not always included in the study of early seismic sequences (e.g. before the year 2000). In addition, other studies only considered short time periods (e.g. a few hours or days) and their catalogs contained a few tens of events, for which it was not statistically meaningful to estimate the $M_C$. Nevertheless, by showing the magnitude of completeness (when available) in the Figures 2b,c (see below), we hope that the potential effect of the magnitude of completeness is now better illustrated.




Lines 87, 280-281: Is there still broad support for the suggestion of EB1995 and their follow-up papers regarding a magnitude-dependent nucleation phase? I thought there were more recent studies that couldn't find evidence for this. It might be good to discuss the latest on this idea somewhere in the paper.

Reply: At present, we do not believe that there is widespread support for a size-dependent nucleation phase. However, we believe that it is important to report that this topic has been investigated in the past. In addition, since foreshocks are ultimately one of the few observables that precede earthquake mainshocks, it is still relevant to understand whether larger collections of datasets will confirm this perspective or reveal other patterns. In this revised version, first we have added a question mark on the Heading of the section 3.1.3 "Mainshock size and foreshock area ?" to better highlight that this is a debate rather than a fact. Also, we have expanded the description of the literature that have previously examined such relationships (e.g. Dodge et al., 1995; 1996; Chen and Shearer 2016; Yoon et al., 2019) and refined the description of our compiled sequences. We have now added additional sentences to report that in recent years, numerical simulations have shown that the earthquake rupture dynamics, and the fault network, stress and strength over a region play a fundamental role in the earthquake propagation and ultimately, on the final mainshock size. Specifically: *"Despite these potential trends between foreshock area and mainshock size, the final mainshock size is also largely controlled by the earthquake dynamic rupture and how it propagates across a fault network (e.g., Okubo et al., 2019)"*

Line 312: replace "resembled" with "suggests that this is the afterslip"?
Reply: Thank you, we have updated the sentence accordingly.

Figure 6a, b: It is quite hard to visualize such space-time scenarios (I have tried and failed myself). Many readers may think the X-axis is also space (i.e., that these are block diagrams, as is Fig. 6c). Would it work better to use color to indicate time? Alternatively, it may be better to get rid of the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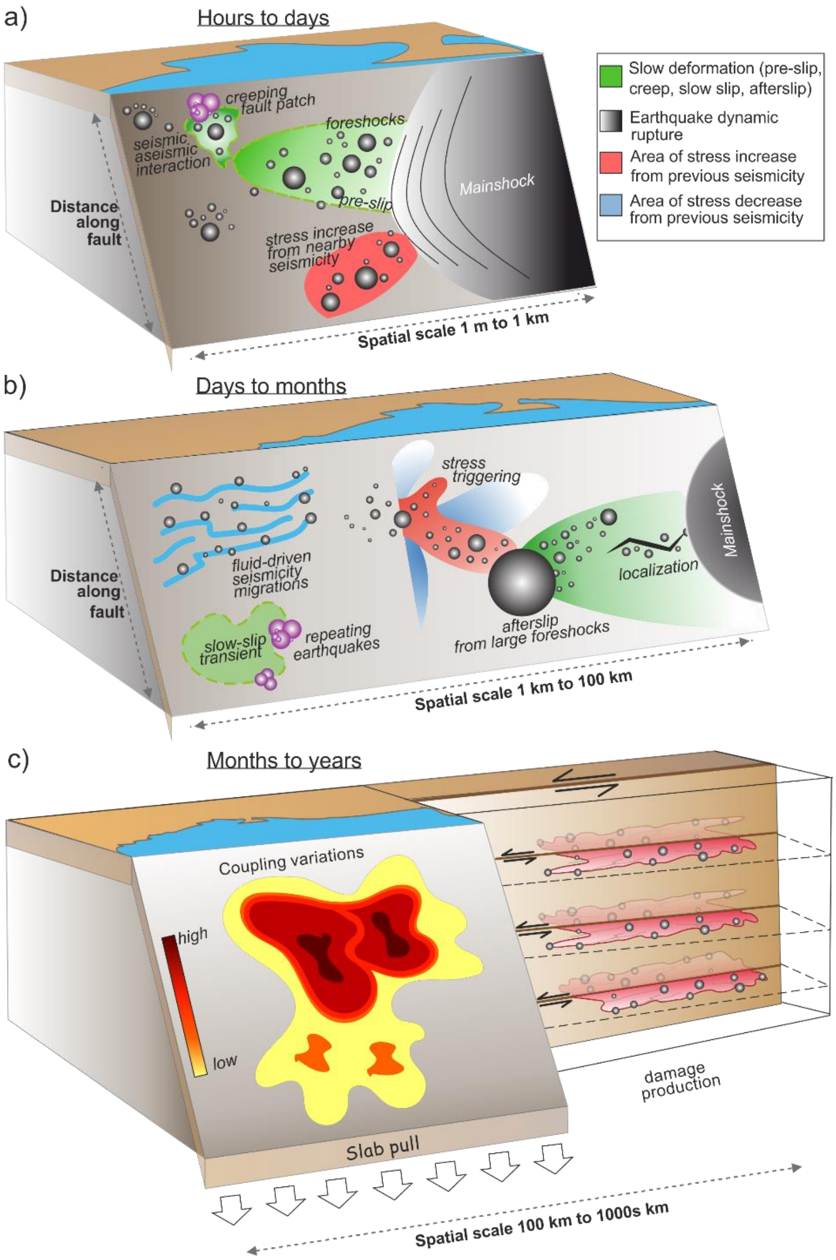
3D "block-diagram" view and present these plots as simple x-time diagrams more analogous to Fig. 1.

Reply: Indeed, the previous panels (a,b) represented to some extent a mixture of spatial and temporal processes. In this version, we have decided to stick to the "block diagram", showing only the spatial description, since the temporal scale is represented anyway with the different snapshots in a),b) and c). However, we prefer to keep the colour coding as in the previous version, as the colour is already encoded with different processes (e.g. aseismic deformation, repeating earthquakes, stress transfer) that also need to be shown. We have modified the figure to better show the spatial scale in (a,b), and additionally added a colour legend.



I found the summaries of all the sequences considered in the supplement very valuable. Could you assign an event number (#1 etc.) to each earthquake and use that in the supplementary table 1 to allow for easy cross-reference.

Reply: Thank you, we have now introduced Events IDs for each of the events, in the Supplementary Text 1 and Table 1, and will refer to them throughout the text when describing individual sequences to facilitate cross-referencing.

**Reviewer #2 (Remarks to the Author):**

The manuscript reviews current theories of earthquake precursory processes and compiles information from published works on observations from 33 earthquake sequences to address the topic. The authors' concluding thesis is that, other than some general sense that stresses increase before a mainshock, the complexity of the processes obscures any potential scaling relationships. While I was very interested to read this contribution because of the topic and the authors' previous work in the field, I don't think the authors' concept came through in the final presentation of the material. I found the manuscript to be difficult to follow, with repetitive sections, cursory explanations of key ideas, and a summary section that seemed more appropriate to a proposal. Unfortunately, I think that it may be necessary to fully re-imagine and re-work the manuscript to make it a suitable publication.

Reply: We thank Reviewer #2 for the critical feedback and for the points that should help us to improve our study. We have taken these general comments very seriously. After carefully reviewing the previous version of the manuscript, we agree that some parts were difficult to follow and contained repetitive information, or we lacked an in-depth description of some essential concepts. With this in mind, we have thoroughly re-worked the entire manuscript and supplementary materials trying to avoid repetition, make the main concepts clearer and easier to follow and provide more fundamental details for essential ideas that may have been incomplete before. As Reviewer #2 mentioned that our concept did not come through, we made a special effort here to describe more specifically throughout the paper one of the common features for all analysed sequences, which is the stress increase in the future mainshock region driven by different processes. Although we have not "entirely re-imagined" the paper, we hope that the strong changes introduced in the manuscript have improved its readability, clarity and coherence.

I provide some additional comments below, but these don't address the broader structural issues with the manuscript noted above.

• Manuscript needs to be edited for English usage throughout.

Reply: This new version of our manuscript has been proof-read by English native speaking colleagues to revise the English usage.

• Analyses of sequences: The plots of compiled sequence behavior (number of events prior to the mainshock, radius of foreshock area) seem difficult to make any interpretations from due to differences in processing choices made by the authors of those studies.

GFZ

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Reply: We understand the reviewer's concern. Regarding Figure 2, which describes the number of events as a function of the time span analysed, the figure is sensitive to the magnitude of completeness and the spatial window considered. In order to show more explicitly the variations in magnitude of completeness between sequences, and following the suggestion of Reviewer 1, we have now, whenever possible, compiled the magnitude of completeness of the catalogues from the different studies, and shown them colour-coded in Figure 2. This illustrates more clearly the differences between standard and enhanced catalogs, and generally shows the greater homogeneity of the enhanced catalogues.

Regarding Figure 4 which shows the foreshock area, we have estimated the additional foreshock areas from the newly compiled catalogues following the approach of Dodge et al., (1996), to make the estimates compatible. We agree that there may still be implicit differences in the magnitude of completeness. However, despite these differences, the figure shows some general patterns that are worth showing and discussing. Nevertheless, we have highlighted these differences in the magnitude of completeness in the text by adding the following:

"*We increased the number of observations with our additional sequences. Although this plot may be affected by the magnitude of completeness and the processing choices made by the different studies, it still shows that, the size of the area activated by the foreshocks does indeed tend to increase with mainshock size (Fig 4), suggesting that aseismic slip may have been involved in mainshock nucleation.*"

Note, however, that in this version we have tried to better reflect the current more skeptical view from the scientific community regarding any potential link in this respect.

• The initial listing of the models is hard to follow because the first two are in a separate bulleted list but the rest are embedded in the middle of paragraphs.

Reply: Thank you, we agree that the previous description of the models was somewhat confusing and the models were mixed between separate paragraphs and embedded in the text. In this new version, we have highlighted the description of the different models as a numbered list, with each model described in a separate paragraph. We hope that this has made Section 2 clearer.

• In several places, the text refers in passing that some interesting info may be in a study rather than just state what it is (i.e. Line 148)

Reply: Thank you for your comment. We have carefully revised the text, focusing on this issue, and correcting possible cases where the important information was unclear or not mentioned (e.g. referring instead to another manuscript). The L.148 mentioned here has been expanded to include the following:

"*Rarely, however, were signals quantitatively linked to intrinsic nucleation processes. A possible exception is the Minto Flats earthquake (Event #19 in Sup. Text 1), where the mainshock was preceded by ~20 s high frequency radiation and a Very Low Frequency (VLF) earthquake, both located near the mainshock hypocenter (Tape et al., 2018).*"

12th Jan 24

Dear Dr Martínez-Garzón,

Your manuscript titled "The complexity of earthquake generation in nature: beyond cascade and pre-slip" has now been seen by our reviewers, whose comments appear below. Reviewer #2 was unable to provide a second report so Reviewer #3 is a replacement. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment under the open access CC BY license (Creative Commons Attribution v4.0 International License).

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Luca Dal Zilio
Editorial Board Member
Communications Earth & Environment

Joe Aslin
Deputy Editor,
Communications Earth & Environment
https://www.nature.com/commsenv/
Twitter: @CommsEarth

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have done a fine job addressing my review comments, and I have no remaining concerns. They have also carried out more substantial revisions in response to some broader criticisms about the presentation of the paper by Reviewer 2. The substantial edits do indeed improve the clarity of the manuscript, but I can't speak for Reviewer 2, who may have additional suggestions.
Roland Burgmann

Reviewer #3 (Remarks to the Author):

The authors followed 33 earthquake sequences and synthesized the common patterns observed from the collection of sequences, with a focus on foreshock activities. They propose that a variety of complex processes interact with each other, leading to the stress increase in the earthquake nucleation region and causing future earthquakes. As a review study, the manuscript is well written with a concise and measured tone. I enjoyed reading it and have a few suggestions that I hope can help the authors improve the manuscript's clarity.

1. One can always propose a more complex model with more parameters. Specifically, the authors propose a conceptual hierarchical model over a wide spatial and temporal range. What is the direct evidence that can confirm the connections between different scales? I would like to see a more rigorous argument that connects the variety of processes and more importantly, provide the context of when and where such models are applicable.

2. Foreshocks are the most obvious slip events shortly preceding the mainshocks. Therefore, investigating the spatiotemporal patterns of foreshocks as well as their source characteristics has long been placed as a focus when investigating earthquake nucleation. However, as noted by the authors, there is a wide range of spatial and temporal scales that have been used to identify foreshocks. Commonly, the scales are used to infer the patterns (then the process). But assuming the hierarchical model proposed by the authors is correct, there can be selection biases when inferring the processes if the scales chosen do not match the actual physical processes. Perhaps the pre-slip model might have an easier way to assign physical meanings to these scales, but the connections between foreshock patterns and other processes are less quantitative. Given the group of sequences the study has followed, I hope the authors can provide some critical assessment on this issue. More importantly, I hope the authors can provide some insights on the physical meanings of the scales.

3. Since it's a review study, the authors might wish to also discuss experiments from Francois Renard's group (microscale characterization of rupture nucleation) and observations from Satoshi Ide's group (hierarchical rupture growth).

4. Oceanic transform faults have shown some of the most regular and systematic precursory behaviors before their characteristic M6 earthquakes, such as events at the East Pacific Rise (McGuire, BSSA, 2003; McGuire et al., Nature, 2005; McGuire et al., Nature Geoscience 2012). I encourage the authors to discuss these observations as well as their models. Oceanic transform faults have much simpler tectonic settings, and discussing earthquake nucleation processes there might help further distinguish the range of mechanisms discussed in the study.

**Reviewer's Comments:**

Reviewer #1 (Remarks to the Author):

The authors have done a fine job addressing my review comments, and I have no remaining concerns. They have also carried out more substantial revisions in response to some broader criticisms about the presentation of the paper by Reviewer 2. The substantial edits do indeed improve the clarity of the manuscript, but I can't speak for Reviewer 2, who may have additional suggestions.
Roland Burgmann

Reply: We thank Reviewer #1 for the constructive evaluation of our work, also reviewing previous versions of this manuscript.

Reviewer #3 (Remarks to the Author):

The authors followed 33 earthquake sequences and synthesized the common patterns observed from the collection of sequences, with a focus on foreshock activities. They propose that a variety of complex processes interact with each other, leading to the stress increase in the earthquake nucleation region and causing future earthquakes. As a review study, the manuscript is well written with a concise and measured tone. I enjoyed reading it and have a few suggestions that I hope can help the authors improve the manuscript's clarity.

Reply: We thank the Reviewer #3 for the constructive review of our paper and for providing comments that we think have helped to improve the manuscript as well as the description of our conceptual model.

1. One can always propose a more complex model with more parameters. Specifically, the authors propose a conceptual hierarchical model over a wide spatial and temporal range. **What is the direct evidence that can confirm the connections between different scales? I would like to see a more rigorous argument that connects the variety of processes and more importantly, provides the context of when and where such models are applicable.**

Reply: Thank you for this comment. In this new version, we have added two paragraphs to the Section 4 - *Summary: A conceptual model for earthquake preparation and nucleation* aiming to address the connection between the different scales. Furthermore, we also explain how numerical modeling and results from experimental studies support our proposed conceptual model. This connection with the experimental and modeling results allowed us to hypothesize about the scenarios in which our model might be applied. In particular, we added the following paragraphs:

"Experimental work, numerical modeling and field observations indicate that the earthquake preparatory process includes damage localization, coalesce of fault segments leading to the failure of larger asperities and enhanced interaction of seismic and aseismic deformation (e.g. Renard et al., 2017; Ben-Zion and Zaliapin, 2020; Cattania and Segall, 2021; Kato and Ben-Zion, 2021; McBeck et al., 2022). Each of these processes leads to variations in the stress field operating at different spatial scales, and reflecting different heterogeneities and temporal evolution over the fault zone.

A multi-scale model for earthquake preparation is also supported by experimental data. Acoustic emissions recorded during rock deformation experiments on rough faults documented that the evolution of the employed seismo-mechanical parameters (e.g. b-value, clustering properties, event proximity, fault plane variability, stress variability, etc) indicated different trends operating at different spatio-temporal scales. This supports the notion of a diversity of physical processes acting juxtaposed at different scales during the earthquake preparatory process (Kwiatek et al., in press). As stress heterogeneities over various lengths are observed to increase with increased roughness and fault heterogeneity, our model might be more representative for seismic sequences occurring on juvenile or segmented fault structures. "

2. Foreshocks are the most obvious slip events shortly preceding the mainshocks. Therefore, investigating the spatiotemporal patterns of foreshocks as well as their source characteristics has long been placed as a focus when investigating earthquake nucleation. However, as noted by the authors, there is a wide range of spatial and temporal scales that have been used to identify foreshocks. Commonly, the scales are used to infer the patterns (then the process**).** **But assuming the hierarchical model proposed by the authors is correct, there can be selection biases when inferring the processes if the scales chosen do not match the actual physical processes**. Perhaps the pre-slip model might have an easier way to assign physical meanings to these scales, but the connections between foreshock patterns and other processes are less quantitative. Given the group of sequences the study has followed, I hope the authors can provide some critical assessment on this issue. **More importantly, I hope the authors can provide some insights on the physical meanings of the scales**.

Reply: We agree with the Reviewer. In fact, we already intended to highlight the potential influence of the selected spatio-temporal window on the inferred physical processes on the first line of Chapter 4. - Summary: *"In the previous sections, we showed that the seismic and geodetic observations that precede mainshocks can be affected by the resolution of the monitoring setup, the choice of temporal and spatial analysis windows and the data processing techniques."*

However, this was perhaps not clear enough. In this version of the manuscript, we have now refined the first paragraph of the Chapter 4 - Summary by adding the sentence: *"Furthermore, the choice of temporal and spatial windows of analysis imprints an upper boundary to the characteristic scales of the physical processes that are possible to resolve".*

With respect to providing some insights on the physical meaning of the scales: we now added a sentence in the section 3.1.3 reporting that, for those sequences that appear to show certain scaling between the mainshock moment and the foreshock area, this length might give some insights about the length at which aseismic slip may occur. Specifically: "the size of the area activated by the foreshocks does indeed tend to increase with mainshock size (Fig 4), suggesting that aseismic slip may have been involved in mainshock nucleation at the spatial scale delimited by the foreshock sequence."

However, we do not necessarily share the view that each of the physical processes may have a fixed characteristic scale over which they operate, and hence we would prefer to not elaborate further on this. The processes are already roughly classified according to their spatial and temporal scale in Figure 5 and conceptually shown in Figure 6.

3. **Since it's a review study, the authors might wish to also discuss experiments from Francois Renard's group (microscale characterization of rupture nucleation) and observations from Satoshi Ide's group (hierarchical rupture growth).**

Reply: We thank Reviewer #3 for these suggestions. The work by F. Renard's group has been added in the Introduction as well as in the Box 1, under the "influence of rock geology on the preparatory process". We have also integrated the results from the work by S. Ide's group on the hierarchical growth of earthquake ruptures under section 3.1.3, which now rea*ds "Can we learn about the upcoming mainshock size from the foreshocks?".* We believe that adding the description of this work has strengthened this section of the manuscript.

4. **Oceanic transform faults have shown some of the most regular and systematic precursory behaviors before their characteristic M6 earthquakes**, such as events at the East Pacific Rise (McGuire, BSSA, 2003; McGuire et al., Nature, 2005; McGuire et al., Nature Geoscience 2012). I encourage the authors to discuss these observations as well as their models. Oceanic transform faults have much simpler tectonic settings, and discussing earthquake nucleation processes there might help further distinguish the range of mechanisms discussed in the study.

Reply: We thank the Reviewer for pointing towards this topic in the literature. We added and discussed the corresponding content along the paper, mainly in the following sections:

- Box 1, on the influence of rock type on the earthquake preparatory process (McGuire et al., 2012).
- Section 2: Definition of the pre-slip model.